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A new control strategy for Active Filters of harmonic voltage using an observer

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ABSTRACT

This paper presents a practical application of a DSP-based current controller for three-phase shunt active filter with a new Control Strategy of voltage harmonics using an observer for measurements of grid impedance. The harmonics will be compensated to a value at PCC (Point of Common Coupling) based on norm EN50160 for low voltage (400 V).

Keywords: Active filters, harmonic isolation, grid impedance measurement, renewable energy systems, digital signal processor.

1. INTRODUCTION

The harmonic cause serious problems in power system which due to non linear loads. It was the solution in many situations: These harmonics adjust to zero [1], [2] that means: The active filter needs sometimes large elements at relatively large currents. So that leads to uneconomic solutions. The article suggests, the individual voltage harmonics will be only regulated to a specified value at PCC for example: 6% for die 5th harmonic at low voltage (based on norm EN50160 [3] and this value must not be exceed.

An observer with measurements of grid impedance has been used to achieve the aim. As a starting point has been assumed that the grid impedance consists of only a resistive portion R and an inductive portion L. It is possible at PCC, which is far from the shunt active filter to calculate the voltage and to renounce a measurement. The proposed method leads to a financial and energy savings.

2. THE SYSTEM CONFIGURATION

Fig.1 shows the system configuration. The system consists of 3 components: a Grid (400 V), a non-linear load and the shunt active power filter.
The load is formed by a diode bridge with resistance and large inductance. The output current of the load generates several harmonics and disrupt the grid. The active filter is a three-phase voltage inverter with control of DC-link voltage. A passive filter has been built on the output of the inverter (Lf=0.5 mH with Rf=10 mΩ, and Cf=15 µF).

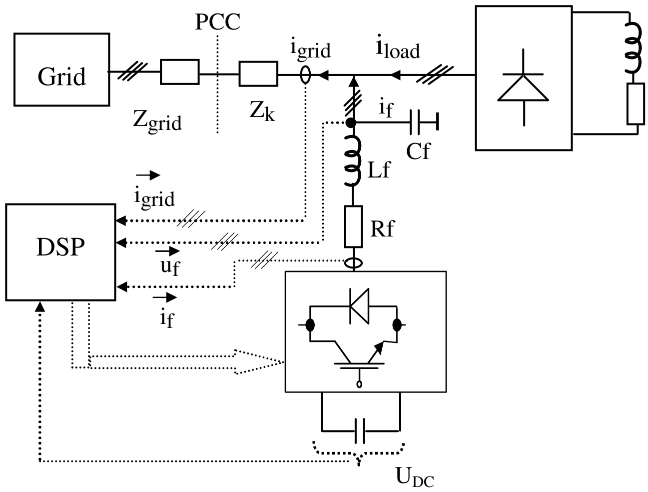

Figure1. System configuration of the three-phase parallel active filter and measurement points

The filter is controlled through DSP 2808 by Texas Instruments (TMS320F2808 32-Bit Digital Signal Controller with Flash, 12-Bit AD-converter, frequency 100 MHZ). The switching-frequency is 16 kHz while the modulation signal is a sawtooth wave.
The DC-link voltage, the currents of the inverter $i_{f(r,s,t)}$, the output voltages of the inverter $u_{f(r,s,t)}$ and currents of the grid have been measured. The shown design inverter can bear up to 20.78 kVA (max. 30 A, 400 V).

3. PROPOSED CONTROL METHOD

This section will deal with the control method for fundamental component of the current, On-line grid impedance measurement and finally the control of the harmonics to a value.

3.1. Control method for fundamental component of the current

The measured voltage $u_{f(r,s,t)}$ are used to determine the grid angle by means of a PLL (Phase-locked- loop). Fig. 2 shows this. The measured currents $i_{f(r,s,t)}$ will be converted using a 3 to 2 transformer (Clarke's transformation) [4] to two AC- values $i_{(\alpha,\beta)}$ and using a Park's transformation ($e^{-\varphi}$) and the PLL-angle (φ_{PLL}). to two DC-values of the currents $i_{(d,q)}$.

$$i_d = i_\alpha \cos\varphi_{PLL} + i_\beta \sin\varphi_{PLL} \quad (1)$$

$$i_q = i_\beta \cos\varphi_{PLL} - i_\alpha \sin\varphi_{PLL} \quad (2)$$

The DC-values of the currents will be controlled using a PI-controller as actual values.
The target values for PI- controller of current consist of two components:
1- The i_q current base value is set to zero.
2- The i_d current is the output value of the PI-controller of the DC-voltage (The DC- voltage is controlled to a constant value using outer loop controller).
The output signal of the current controller is converted to the grid-coordinate-system using a Cartesian-Polar-converter and the PLL-angle. The phase and amplitude will be decomposed using a 2 to 3 transformer to three components.
In the final stages the 3 signals go into the modulator.

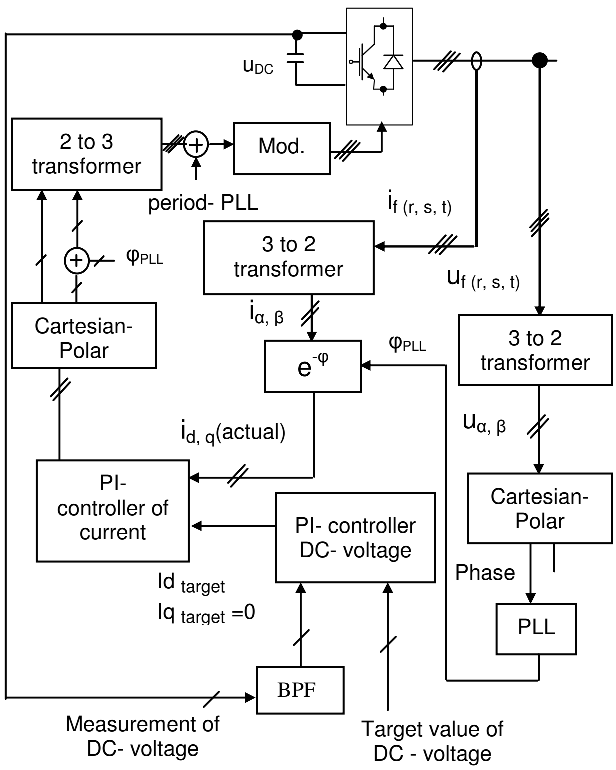

Figure2. Control method for DC-voltage, and fundamental component of current in a block- diagram form.

3.2. Grid impedance measurement

Fig.3 shows the single-phase equivalent circuit of the three-phase system. The inverter is connected as voltage source at the grid with a resistance R and an inductance L. R and L are the real- and imaginary components of the grid impedance.

$$Z = R + j\,w\,L \tag{3}$$

Several harmonics h_i can occur in a three phase system with non–linear load,:

$$i = 6N \pm 1 \quad \text{with} \quad N:1, 2, 3... \tag{4}$$

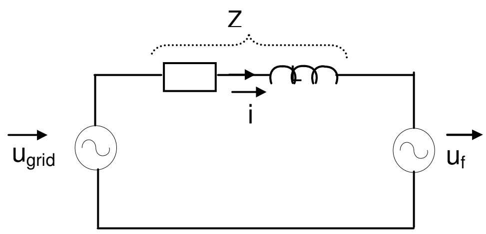

Figure3. single- phase equivalent circuit of three-phase system

The harmonics are the h_5, h_7, h_{11}, h_{13} etc. They correspond to the frequencies 250, 350, 550, 650 Hz etc. The impedance has been calculated though a simple principle as in (5):

$$Z = \frac{\Delta \vec{u}}{\vec{i}} = \frac{\vec{u}_{grid} - \vec{u}_f}{\vec{i}} \tag{5}$$

The problem is the following: The grid is often distant from the inverter. As a consequence, the voltage grid is not measured and the $\Delta\vec{u}$ over Z cannot be determined.
The proposed solution is the following: feeding another frequency into the grid using the shunt active power filter. The frequency (i.e. the current and voltage at this frequency) occurs not in the normal situation. Several measurements are carried out with different frequencies from 25 Hz to 1000 Hz with steps of 50 Hz Fig.10. The reason for feeding the 75 Hz is that 75 Hz is the least negative sequence voltage (about zero) in U_{grid}.

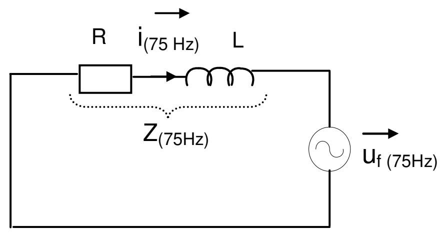

Figure4. single- phase equivalent circuit of three-phase system with 75 Hz

The differential equations are:

$$\vec{u}_{f(75Hz)} = R \cdot \vec{i}_{f(75Hz)} + L \cdot \dot{\vec{i}}_{f(75Hz)} \tag{6}$$

$$\vec{u}_{f(75Hz)} \cdot e^{(-j\omega t)} = R \cdot \vec{i}_{f(75Hz)} \cdot e^{(-j\omega t)} + L \cdot \dot{\vec{i}}_{f(75Hz)} \cdot e^{(-j\omega t)}$$

whereas:

$$\vec{i}_f = \vec{i}'_f \cdot e^{(j\omega t)} \Rightarrow \dot{\vec{i}}_f = \dot{\vec{i}}'_f \cdot e^{(j\omega t)} + j\omega \vec{i}'_f \cdot e^{(j\omega t)} \tag{8}$$

$$\vec{u}'_{f(75Hz)} = R \cdot \vec{i}'_{f(75Hz)} + L \cdot (\dot{\vec{i}}'_{f(75Hz)} + j\omega \vec{i}'_{f(75Hz)}) \tag{9}$$

The dash (') denotes the value in a dq- coordinate system.

In the stationary state is $\quad \dot{\vec{i}}_{f(75Hz)} = 0 \qquad (10)$

This leads to the following simplification:

$$\vec{u}'_{f(75Hz)} = R \cdot \vec{i}'_{f(75Hz)} + L \cdot j\omega \vec{i}'_{f(75Hz)} \tag{11}$$

The individual components follow:

$$u_{f\,d(75Hz)} = R \cdot i_{f\,d(75Hz)} - \omega_{(75Hz)} L \cdot i_{f\,q(75Hz)} \tag{12}$$

$$u_{f\,q(75Hz)} = R \cdot i_{f\,q(75Hz)} + \omega_{(75Hz)} L \cdot i_{f\,d(75Hz)} \tag{13}$$

$$i_{f\,q(75Hz)} = 0 \Rightarrow$$

$$R = \frac{u_{fd(75Hz)}}{i_{f\,d(75Hz)}} \tag{14}$$

$$\omega_{(75Hz)} L = \frac{u_{fq(75Hz)}}{i_{fd(75Hz)}} \tag{15}$$

3.2.1 Realization of Grid impedance measurement

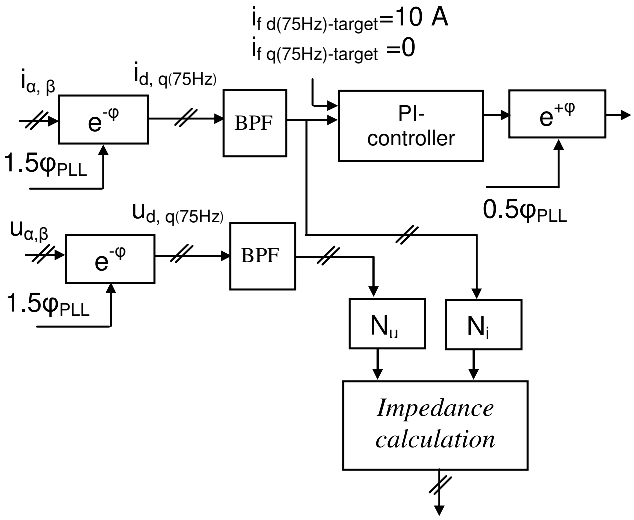

Figure5. Block diagram of Grid impedance measurement with 75 Hz

The Fig.5 shows the idea in the impedance calculation. The $i_{d\ (75\,Hz)}$ is controlled at 10 A and $i_{q\ (75\,Hz)}$ to zero. The PLL- angle turns with 50 Hz. Thus the 75 Hz arises as DC-values with a band-pass filter (BPF)and using a Park's transformation 1.5 times of the PLL- angle Fig.11.

After the controller the AC- values will be used.

$$u_\alpha = u_d \cos 0.5\varphi_{PLL} - u_q \sin 0.5\varphi_{PLL} \tag{16}$$

$$u_\beta = u_d \sin 0.5\varphi_{PLL} + u_q \cos 0.5\varphi_{PLL} \tag{17}$$

This Signal is added to the output signal of the PI- current controller in Fig. 2.

N_i and N_u is current-standardization-factor and voltage-standardization - factor for the calculation in the DSP.

The injection current ($i_{f\ d(75Hz)\text{-target}}$) is determined less than what exists in norm for 75 Hz.

3.3. Control method of 5th harmonic to a certain value

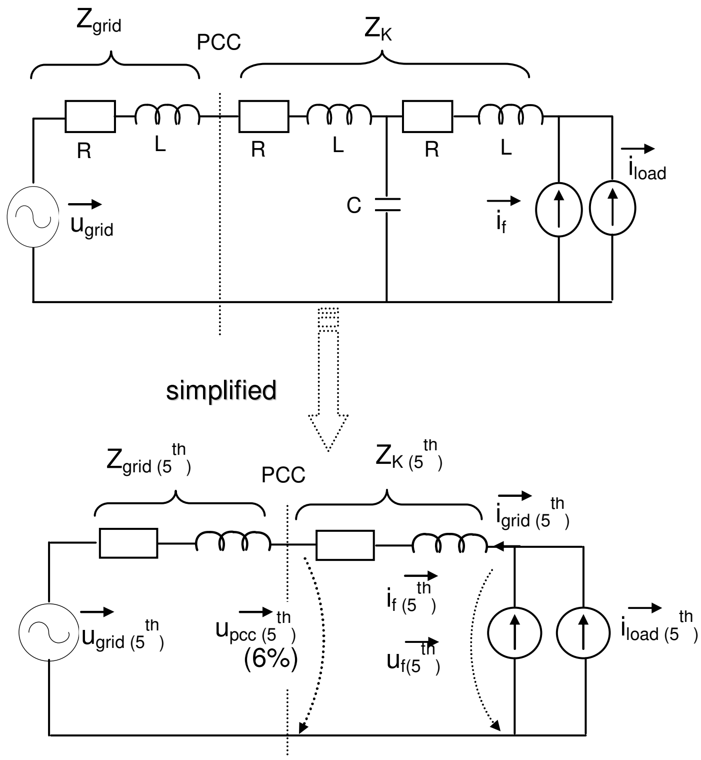

Figure6. Single- phase equivalent circuit with respect to 5th harmonic.

Fig. 6 shows the single- phase equivalent circuit of the Fig.1. The load (with a large inductance) and the inverter are shown as current sources. Although the inverter is a voltage source, it can be regarded as current source in case of a fast current control.

The cable impedance Z_K is shown in Fig.6 up as T-element. Since C is very small, C has been neglected and it remains only an R L – element for Z_K.

According to the norm[3] 6% of the nominal voltage-Vn=400 V is the allowable value amplitude of the 5th voltage harmonic at the PCC. The control has been built at this value. This value must not be exceeded.

The phase-shift of the current grid for the 5^{th} harmonic $i_{grid(5^{th})}$ must be equal to the current load fort the 5^{th} harmonic $i_{load(5^{th})}$, so that the least the compensating current it is used.

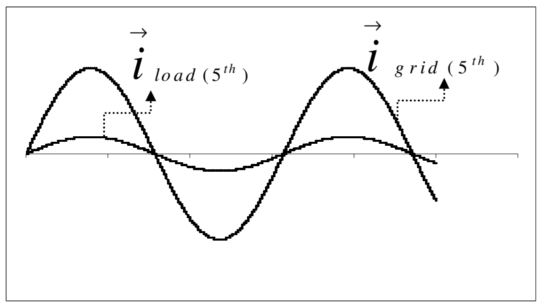

Figure7. Load current and Grid current of 5thharmonic

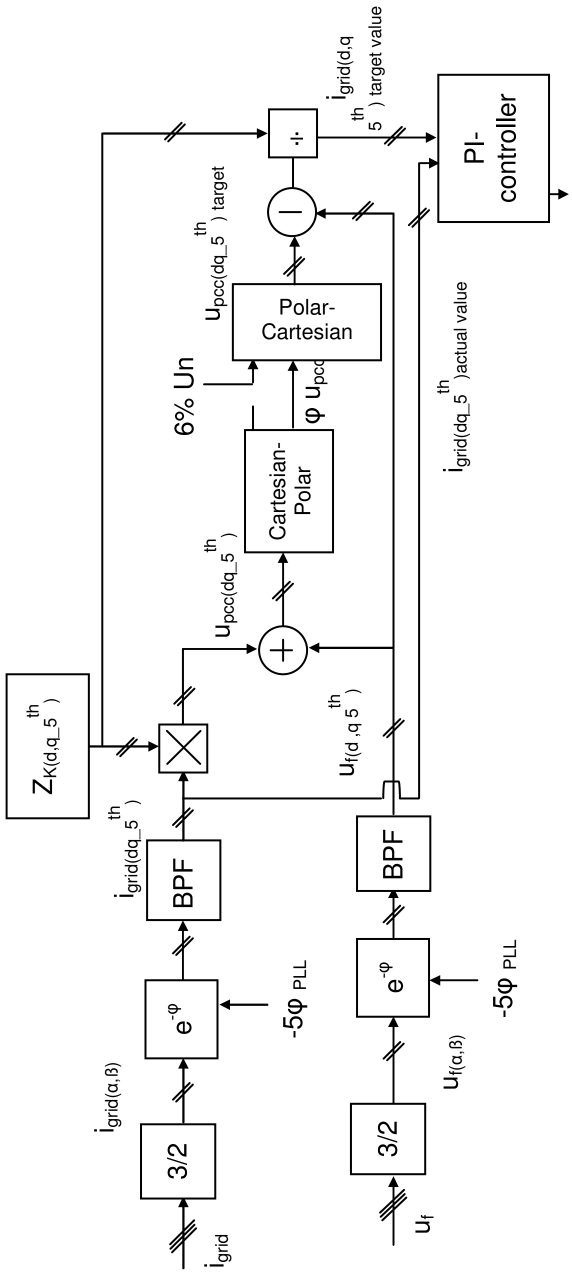

Figure8. The control of 5^{th} harmonic to a certain value in a block-diagram form

The Point of Common Coupling (PCC) acts as a voltage divider. Fig.6 yields the reference equations so:

$$\vec{i}_{grid(5^{th})} = \vec{i}_{f(5^{th})} + \vec{i}_{load(5^{th})} \tag{18}$$

$$\vec{u}_{pcc(5^{th})} = \vec{Z}_{K(5^{th})} \cdot \vec{i}_{grid(5^{th})} + \vec{u}_{f(5^{th})} \tag{19}$$

$$\vec{u}_{pcc(5^{th})} = \vec{u}_{grid(5^{th})} - \vec{Z}_{grid(5^{th})} \cdot \vec{i}_{grid(5^{th})} \tag{20}$$

$$\vec{u}_{grid(5^{th})} = (\vec{Z}_{grid(5^{th})} + \vec{Z}_{K(5^{th})}) \cdot \vec{i}_{grid(5^{th})} + \vec{u}_{f(5^{th})} \tag{21}$$

A current control system for the amplitude and phase is not stable enough. This is why it has been built a control in a dq- coordinate system.

Using the reference equations the target value for current $i_{grid(5^{th})}$ for a given value $u_{f(5^{th})}$ and the voltage at PCC u_{pcc} can be generated. Fig. 8 shows the required block structure.

Note: the grid impedance is very small in the laboratory. For this reason it has been used additional impedance, so that the grid can have sufficient voltage harmonics and the regulation method can be tested.

This paper discussed the control method of the 5^{th} and $h7^{th}$ harmonic. For the 11^{th} and 13^{th} to 25^{th} harmonics it is also possible.

In the laboratory both will be regulated at the half of the norm value, which means the 5^{th} to 3% and the 7^{th} to 2.5%.

4. EXPERIMENTAL RESULTS

In the remainder of the paper, we present selected results.

Fig. 9 shows the output signal of the PI-controller in Fig. 2 for the control of the fundamental component.

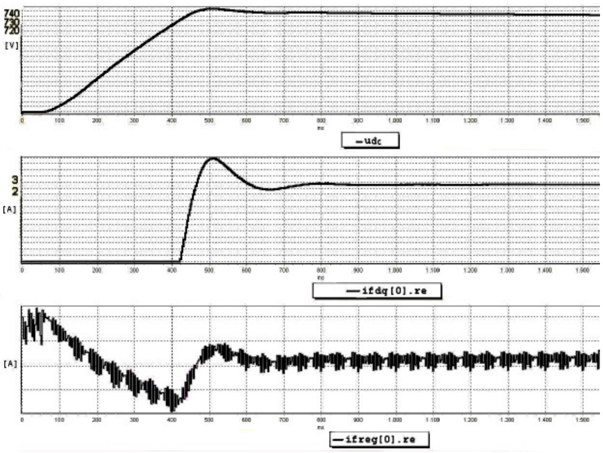

Figure9. (1) charge of DC-voltage, (2) Regulation of DC-voltage, (3) control of fundamental component (filter current)

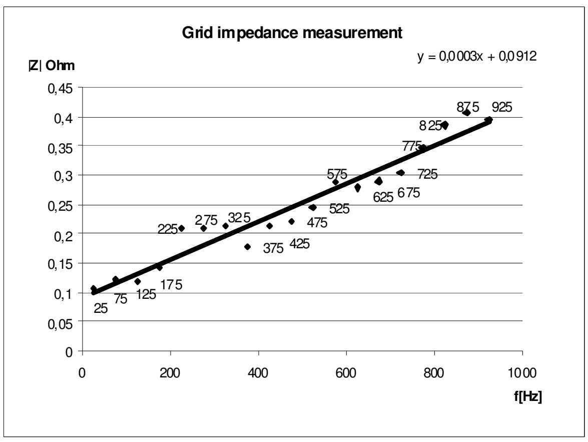

Figure10. Grid impedance measurement for Frequencies from 25 Hz to 1000 Hz with steps of 50 Hz

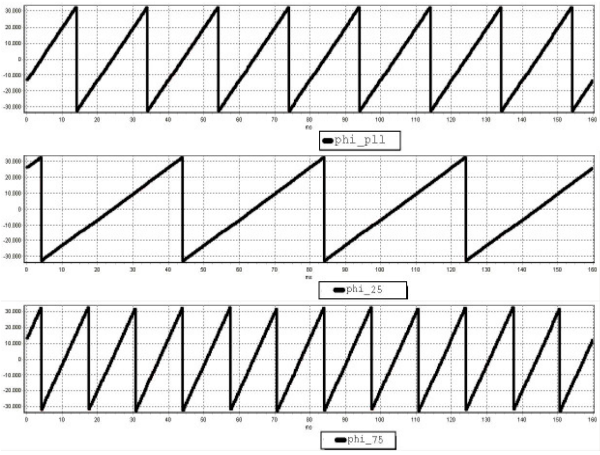

Figure11. Ratio between the PLL-angle and the angle of 75 Hz-Signal using 25 Hz

The following results were measured with an oscilloscope (300 MHz, 2GSa/s).

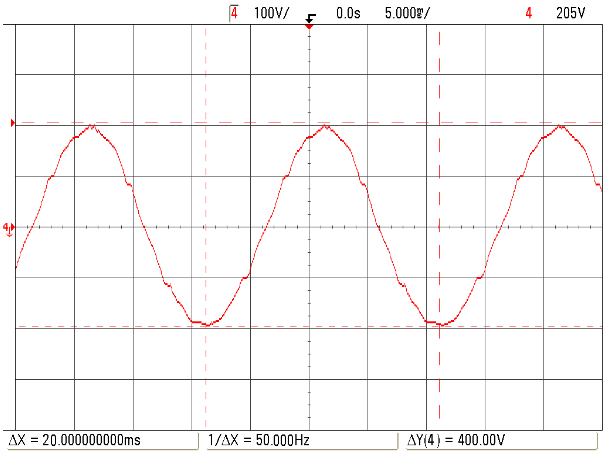

Figure12. Voltage at PCC with the regulation (5h to 3%, 7h to 2.5%)

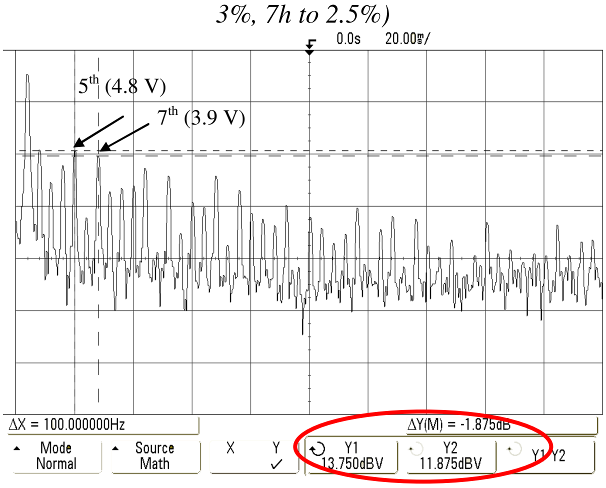

Figure13. Fourier analysis of the voltage harmonics with regulation to a specific value at PCC (5^{th} to 3%, 7^{th} to 2.5%)

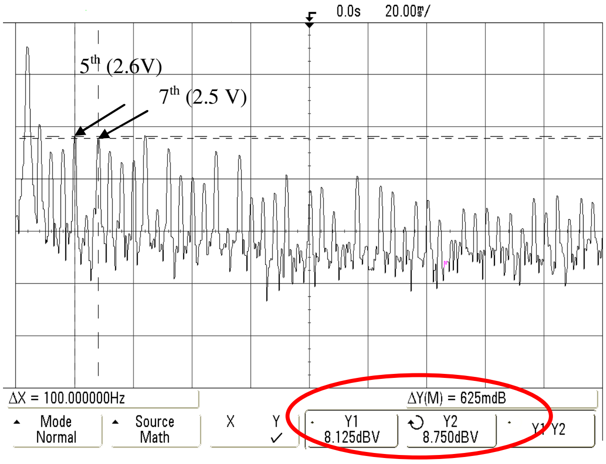

Figure14. Fourier analysis of the voltage harmonics with regulation to a specific value at PCC (5^{th} and 7^{th} to 1. 7%)

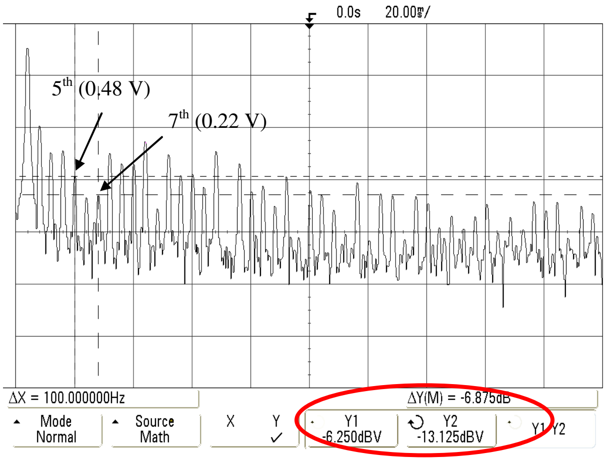

Figure15. Fourier analysis of the voltage harmonics with regulation to zero at PCC (5^{th} and, 7^{th} to zero)

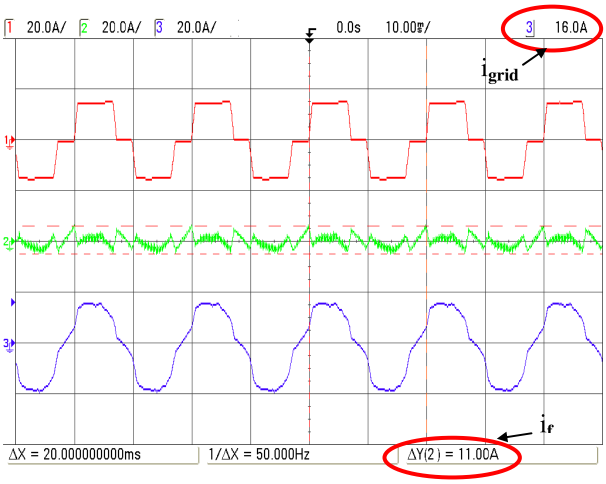

Figure16. Load current (red), compensating current (green) and grid current (purple) at PCC (5^{th} to 3%, 7^{th} to 2.5%)

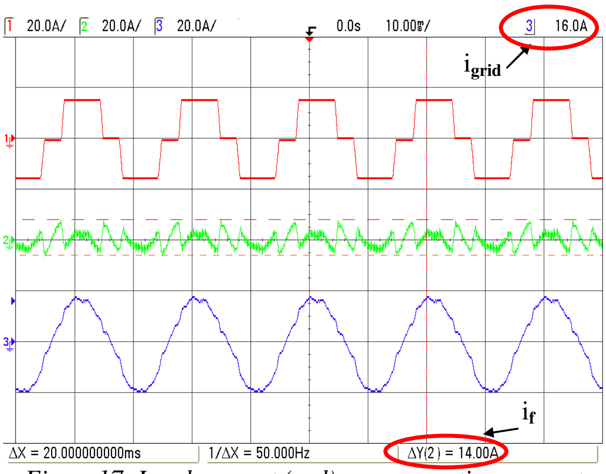

Figure17. Load current (red), compensating current (green) and grid current (purple) at PCC (5^{th} and 7^{th} to 0%)

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5. CONCLUSION

The control of the harmonics is important, but it costs a lot of energy and money. Therefore, we can optimize this case if we control the harmonics only at a norm value and not always at zero. Part of the control strategy is an observer with Online-grid impedance measurement.

if the impedance is determined, It is possible by active filter the harmonics to control not only at the connected point but also at another place.

The paper presents a control method through which no further measurements are needed.

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